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A NdYAG laser with a 600 W output power was procured and installed. Thermal defocusing in the laser's NdYAG rod suggested that the beam quality and power density were highest at about 400 W, rather than the full 600 W power leavel. The laser heated cathode system was installed on the MELBA diode. The ceramic insulator stack has been designed, fabricated and vacuum tested. It employs 12 ceramic rings alternating with Kovar rings which are cacuum brazed together.

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May 1999

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Executive Summary

This report documents the research and development performed concerning ultraclean high power microwave sources. There were two parts of this research:

1) Laser-heated LaB_6 thermionic cathode research and

2) development of a ceramic insulator for the MELBA e-beam generator.

On the first project, a NdYAG laser with a 600 W output power was procured and installed. This laser was utilized for two series of experiments. The first feasibility experiments were performed in a cryopumped cathode test chamber. These experiments measured cathode temperature as a function of laser heating power for several cathodes and geometries. It was found that the laser power was sufficient to reach temperatures (1600-1700 C) at which LaB_6 thermionic emission could be sustained. Thermal defocusing in the laser's NdYAG rod suggested that the beam quality and power density were highest at about 400 W, rather than the full 600 W power level. This was borne out in further experiments. Low voltage (kV) electron beam extraction experiments were also performed in the cathode test chamber. Finally, the laser heated cathode system was installed on the MELBA diode. Experimental results demonstrated peak thermionic currents up to about 90 A; or a current density of nearly 70 A/cm^2. In addition to the "pure thermionic" mode of operation two other cathode modes were observed: plasma mode and combined thermionic/plasma mode. The plasma mode was characterized by rapid current ramping (up to 4 kA), indicative of diode closure. The combined thermionic/ plasma mode apparently started as thermionic current, but transitioned to the rapidly ramping plasma current at later times. The plasma mode and combined thermionic/ plasma mode probably results from electric field enhancement, above the threshold electric field for explosive/ field emission. The results presented here are submitted to a book on MURI accomplishments.

The ceramic insulator stack has been designed, fabricated and vacuum tested. It employs 12 ceramic rings alternating with Kovar rings which are vacuum brazed together. Fabrication required overcoming a number of challenges in metallizing and brazing such large diameter (~40 cm) rings. Stainless steel field shaping, grading rings and grading resistors are employed to account for the fact that the ceramic rings are straight-cut tubes.

1.0 Equipment Purchased

Vendor Information for Equipment

NdYAG Laser (650 W CW) =$65,400
from US Laser Corp.
825 Windham Court North, Wyckoff, NJ 07481
Phone (201) 848-9200
FAX (201) 848-9006
Quotation #2978
by James F. Golden, VP Marketing
August 22, 1996

Ceramic Insulator Stack = $167,000
Pulse Sciences Inc./ Titan Technologies
600 McCormick St.
San Leandro, CA
Phone (510) 632-5100 (X305)
FAX (510) 632-5300
quotation No. 96-824b
Contact: Janet Luna (ext. 209)

*All prices reflect discounts to University of Michigan

2.0 DURIP Results

2.1 Laser Heated Lanthanum Hexaboride Cathodes

Lanthanum hexaboride is an attractive cathode material because it is relatively immune to poisoning, exhibits low work function (Φ~2.4-3 eV) and high current density. For intense e-beam microwave sources, the major advantage of high current, thermionic cathodes is long-pulse capability by elimination of plasma diode closure. Relevant applications of LaB_6 cathodes include gyrotrons and relativistic magnetrons. One of the drawbacks of LaB_6 has been that it is typically fabricated from ceramic pellets cut from a sintered rod and therefore, is difficult to heat uniformly.

Experiments have been performed utilizing NdYAG laser-heating of LaB_6 cathodes in a MV accelerator e-beam diode. The laser provides uniform surface heating and eliminates the need for a MV isolation transformer. The experimental configuration is depicted in Fig. 1. The CW NdYAG laser beam is slightly focused by adjusting the internal collimator optics. Output powers of the NdYAG as high as 650 W were achieved. It was found that the size of the laser spot grew quite large at the highest powers due to thermal gradients in the NdYAG rod. Laser power was typically adjusted up to 600 W by varying the flashlamp current.

Initial laser heated cathode temperature experiments were performed in a cryopumped stainless steel vacuum chamber. Later experiments were performed on the cryopumped MELBA diode at base pressures on the 10^{-6} Torr scale. Initially, the cathode was mounted on a low thermal-conduction holder with a boron-nitride (insulating)

baseplate. A fiberoptic probe was utilized for transmission of cathode light to the optical pyrometer and also to a 0.75 m optical spectrograph. A 1.06 micron-wavelength, line-blocking filter was utilized to filter out laser light from the pyrometer and spectrograph; this slightly changed the calibration of the pyrometer.

Several sizes of LaB_6 cathode pellets were utilized: 2.2 cm and 1.3 cm diameter disks and an irregular, sector/ wedge piece with a width of about 1 cm. Temperatures were estimated from both the optical pyrometer and the visible optical spectroscopy of the blackbody spectrum. The pyrometer measurements of cathode temperature are presented in Fig. 2. It can be seen that the smallest cathode achieved the desired range of 1,700 C temperatures for LaB_6 with laser power as low as 300 W, while the larger (2.2 cm dia) cathode reached a lower temperature, approaching 1,500C at nearly 600 W. This was believed to be due to the degradation of the laser beam power density due to thermal gradients in the NdYAG rod.

High energy electron beam current generation experiments of the laser heated LaB_6 cathodes (2.2 cm and 1.3 cm diameter disks) were performed on the diode of the MELBA accelerator with a flattop voltage of about -0.8 MV (Fig. 3a). It was found that there exist at least three operating modes for the laser-heated LaB_6 cathodes in the MELBA accelerator, depending upon the laser-heating power and cathode geometry.

1) thermionic mode at electron beam current densities typically at about 60-70 A/cm^2, with current shape which matches the cathode voltage,

2) Plasma mode, in which the kA current rapidly ramps upward, and
3) Combined, thermionic/ plasma mode in which the initial thermionic current turnon, is later overtaken by plasma current.

An example of each type of cathode current is presented in Figure 3. In the pure thermionic mode (Fig. 3b) it can be seen that this current follows the voltage with a peak of about 90 A; there exists no evidence of current ramping. The laser heating power was about 400 Watts for this pulse. In the plasma mode, the rapid plasma closure is obvious by the strongly ramping current (Fig. 3c); this pulse had a laser heating power of 200 Watts, which was too low for thermionic emission. In other cases with some 600 W of laser power, the plasma mode was also observed. This was believed due to LaB_6 evaporation from overheating (>1700 C), which caused plasma. The combined thermionic/plasma mode, (shown in Fig. 3d) was characterized by a moderate, initial current, apparently thermionic, which followed the voltage; this current was subsequently overwhelmed by ramping current which is probably due to plasma. It is believed that these cathode holders had edges where the electric field exceeded the threshold for cold cathode field emission (>160 kV/cm).

Several other points should be made regarding laser-heated LaB_6 cathodes. The vacuum of these experiments was only in the range of 10^{-6} Torr, which would be inadequate to avoid poisoning conventional oxide cathodes. Note that LaB_6 can be poisoned if the anode (which ablates) is made of a incompatible material (e.g.,

titanium); (possibly observed in early UMi experiments). For this reason anodes were made of carbon in the later UMi experiments. Finally, one needs to avoid overheating of LaB_6 to minimize evaporation, which can coat adjacent areas near the cathode intended to be nonemitting.

In summary, we have demonstrated for the first time that lanthanum hexaboride cathodes can be heated by a laser to emission temperatures in a MV electron beam diode. These data demonstrate the importance of operating LaB_6 cathodes below the field/ explosive emission threshold electric field. Operation above this threshold E field results in the measured, rapidly-increasing plasma current closure or the combined thermionic/ plasma mode. Future experiments will address this issue by cathode designs which minimize edge enhancement of electric fields and by operation at lower cathode voltages.

2.2 Ceramic insulator Stack

A ceramic insulator stack has been designed and fabricated at Pulse Sciences, Inc. (PSI) in San Leandro, California. This insulator is designed to be utilized as a direct replacement/ upgrade on the Michigan Electron Long Beam Accelerator (MELBA) at the University of Michigan, at parameters V= -1 MV, I = 1-10 kA, and pulselength = 1 microsecond. A schematic illustration of the design is presented in Figure 4. Straight-cut ceramic tubes were employed because of their availability in the large diameters (~40 cm) required. The brazed rings between the alumina rings are made of Kovar because of its compatibility to alumina. Contoured stainless steel grading rings are employed to shape the electric field. Voltage dividing resistors are also employed on the oil side of the insulator to ensure equal grading of the electric field.

A photograph of the completed insulator assembly is presented in Figure 5. The major challenge of the development program at PSI was the ceramic metalization and brazing together of the ceramic and Kovar rings. After many setbacks, this task was successfully completed and testing at PSI showed hermetic seals after the braze. End flanges were e-beam welded on. Because the ceramic insulator is longer than the plastic insulator it replaces, an extension spool piece needed to be fabricated to extend the MELBA oil tank.

3.0 Publications Resulting from this Research

1) High Power Microwave Research (MURI) Book, edited by Robert Barker and Edl Schamiloglu, IEEE Press, in preparation, (Much of this report is contained in a contribution to the cathode chapter of this book).

2) Laser-Heated Thermionic Cathodes for Long-Pulse Electron Beam Generation, D.E. Vollers, R.M. Gilgenbach, R.L. Jaynes, M.D. Johnston, W.D. Getty, J.M. Hochman, W.E. Cohen, J.I. Rintamaki, C.W. Peters and T.A. Spencer, 1998 Meeting of the Division of Plasma Physics of the American Physical Society, presented in New Orleans in Nov. 1998, abstract published in the Bulletin of the American Physical Society

3) "Laser Heated LaB_6 Thermionic Cathode on a MV Electron Beam Accelerator ", R.M. Gilgenbach, D. Vollers, R. Jaynes, J. Rintamaki, M. Johnston, W. Cohen, W.D. Getty, Y.Y. Lau and T.A. Spencer, abstract submitted for presentation at the 1999 IEEE International Conference on Plasma Science, June 1999, Monterey, CA

4.0 Graduate Student Training

A number of students have used and are utilizing this DURIP equipment:

1) Doyle Vollers, Captain, USAF, thermionic cathode, graduated: MS

2) Mark Johnston, graduate student, thermionic cathode

3) Bill Cohen, graduate student, optical spectrum,

4) Jon Hochman, graduated: Ph.D.

5) Reggie Jaynes, graduate student

6) Mike Lopez, graduate student

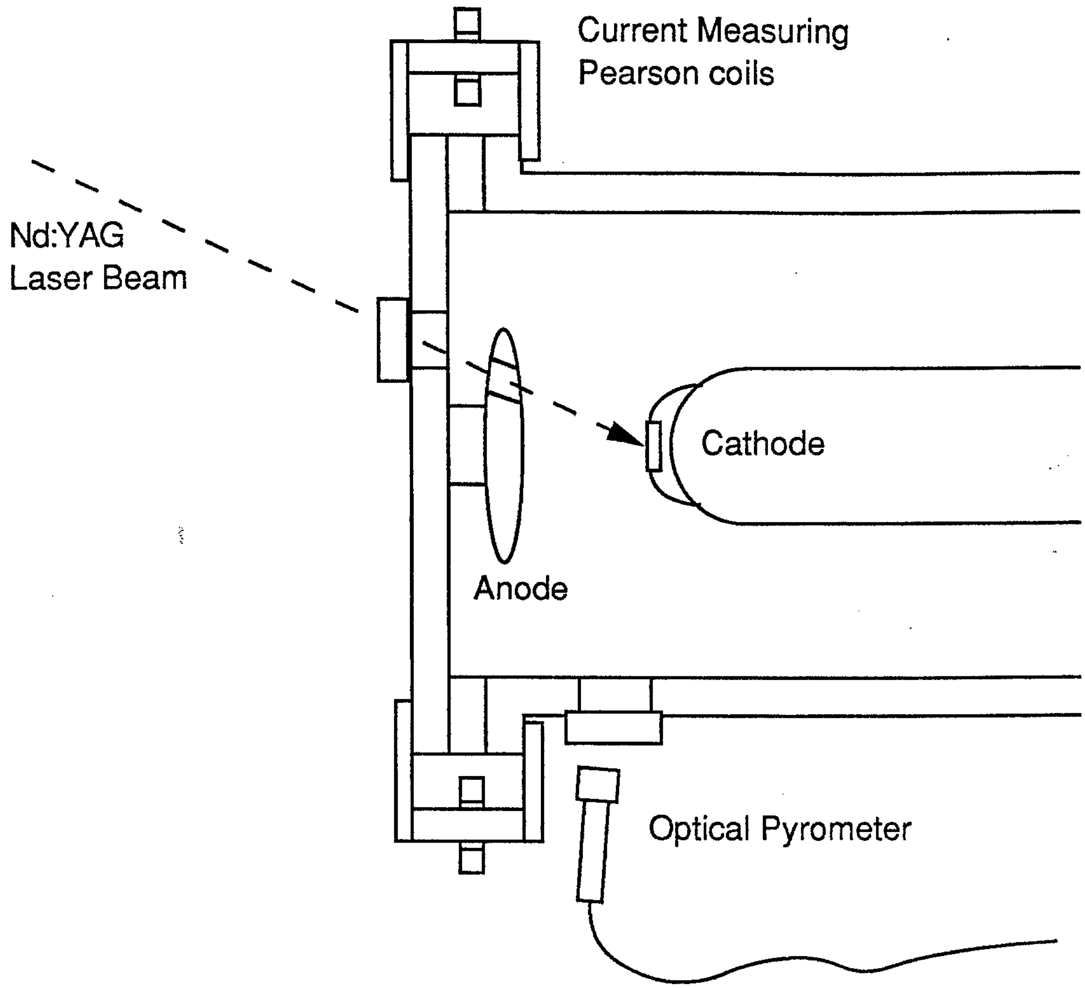

Fig. 1. Experimental configuration for laser-heated LaB_6 cathode.

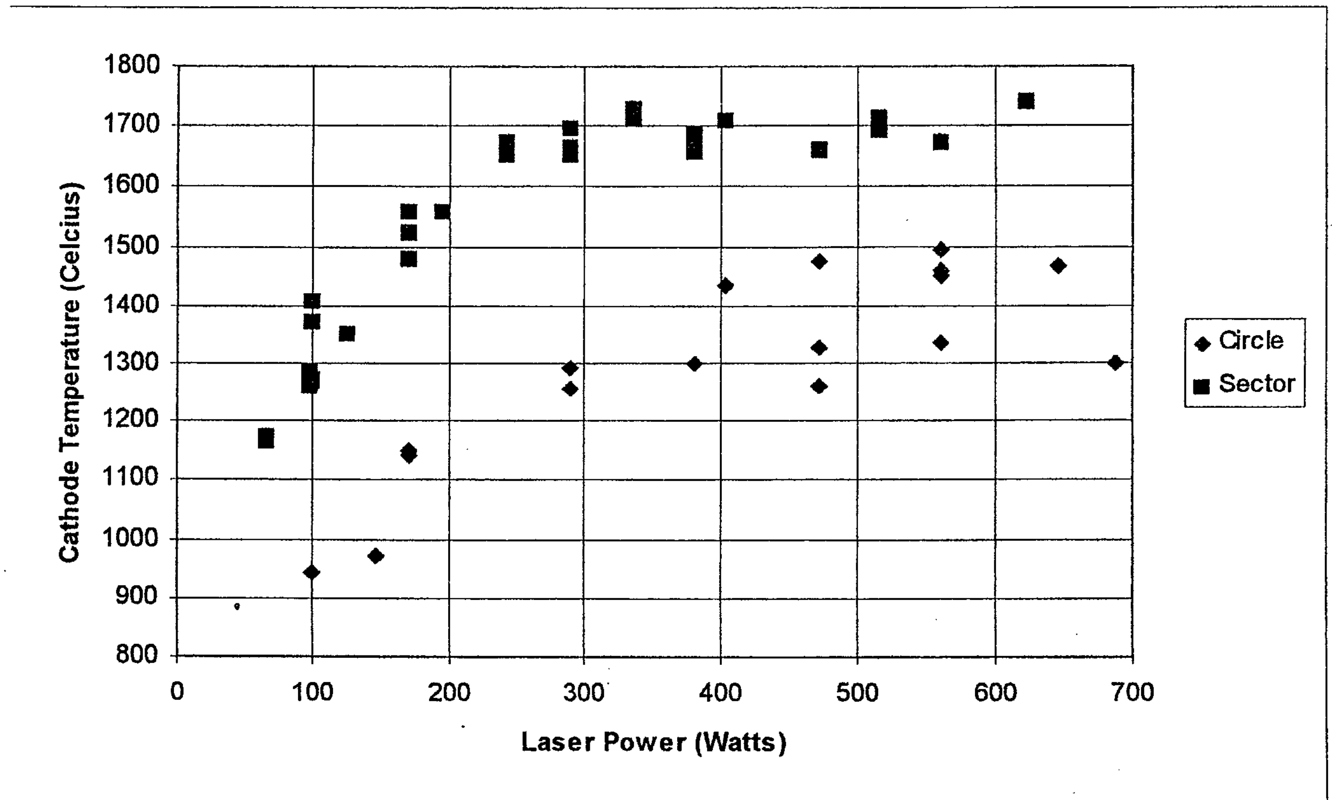

Fig. 2. Temperature of LaB_6 cathodes as a function of NdYAG laser-heating power. LaB_6 circle is 2.2 cm in diameter. The sector is a wedge with a length of about 1 cm.

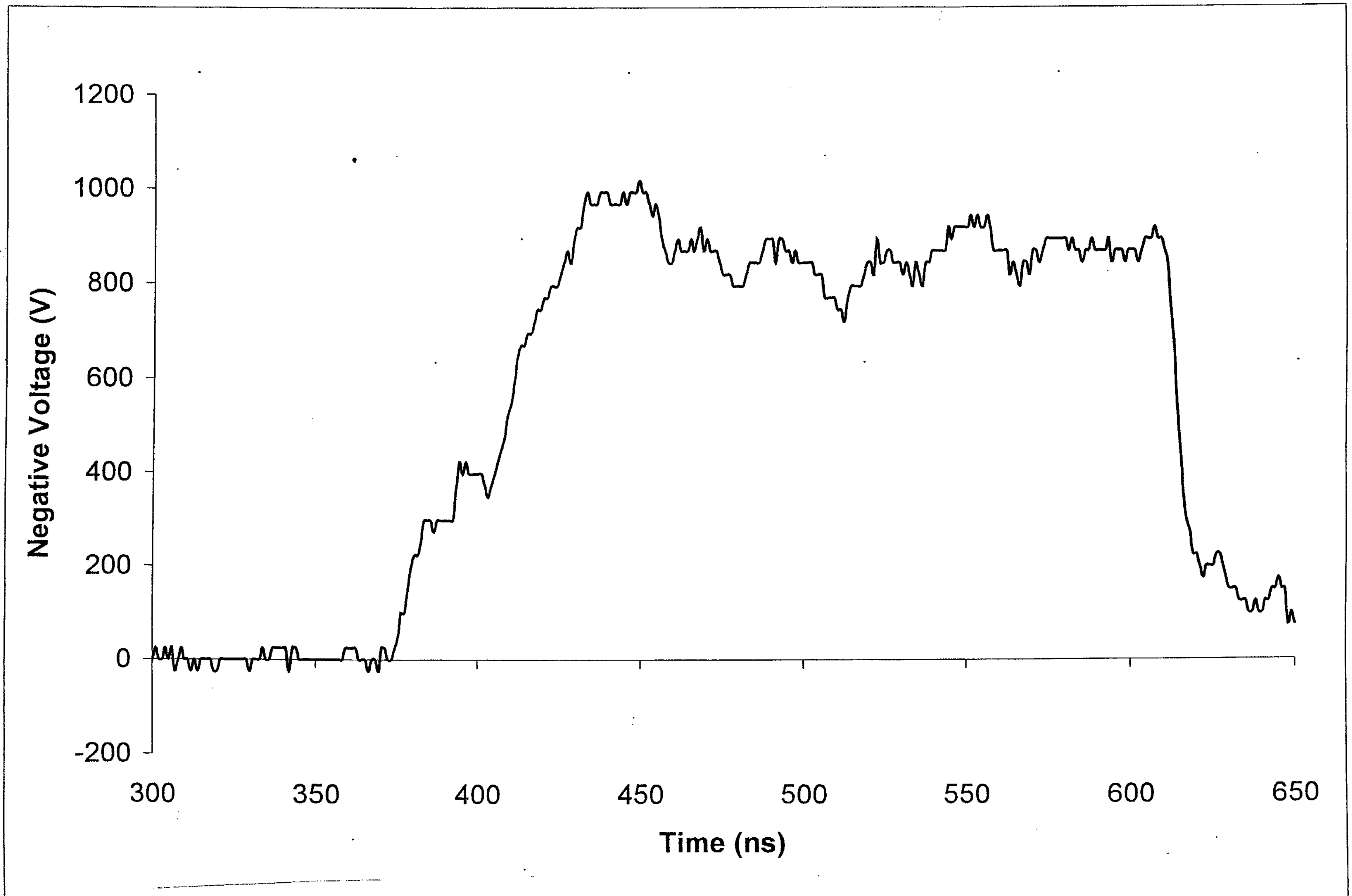

Fig. 3. MELBA diode signals:
a) cathode voltage (negative),

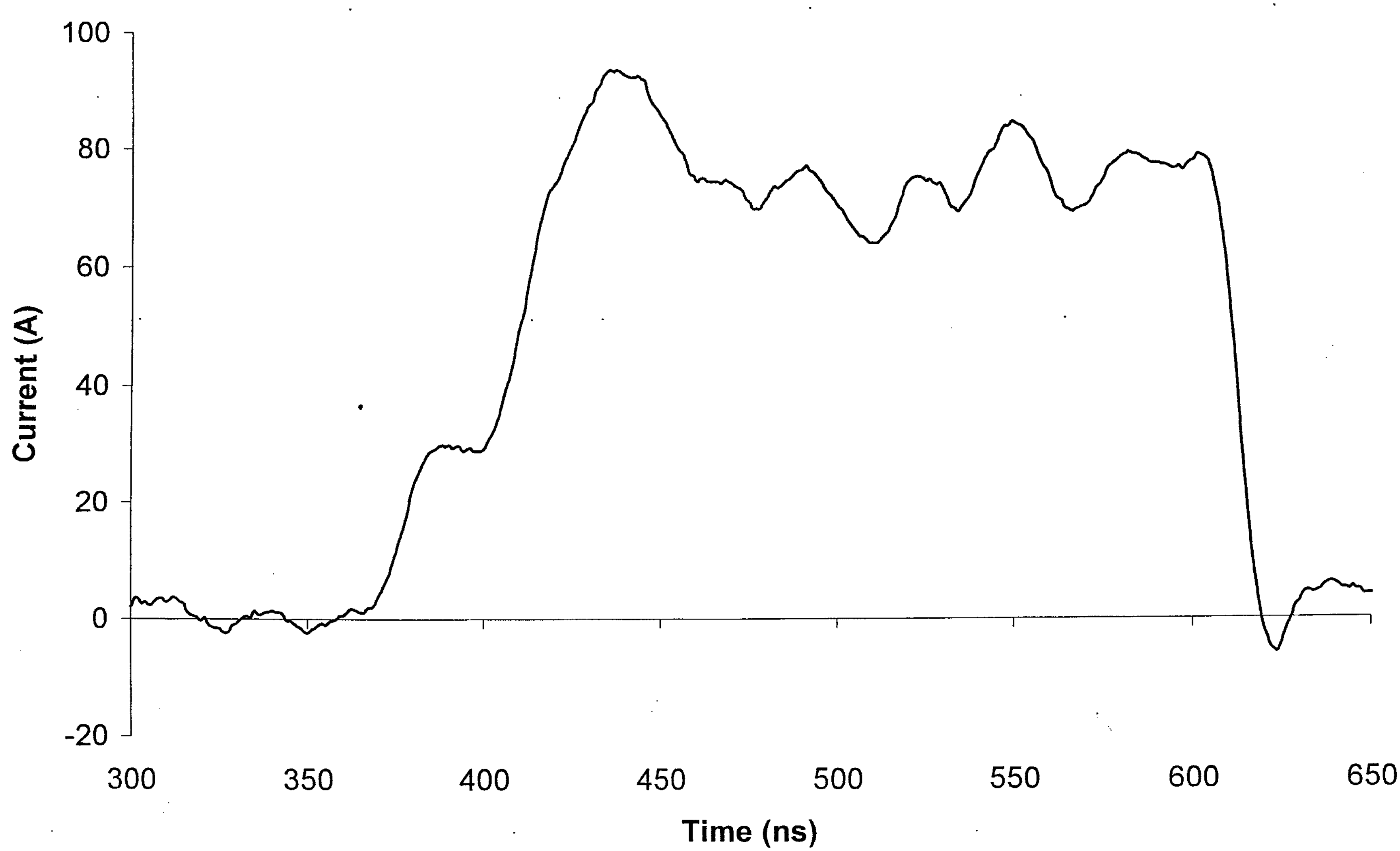

Fig. 3.) b) e-beam current measured at anode (digitally smoothed) for: pure thermionic mode (laser power of 400 W),

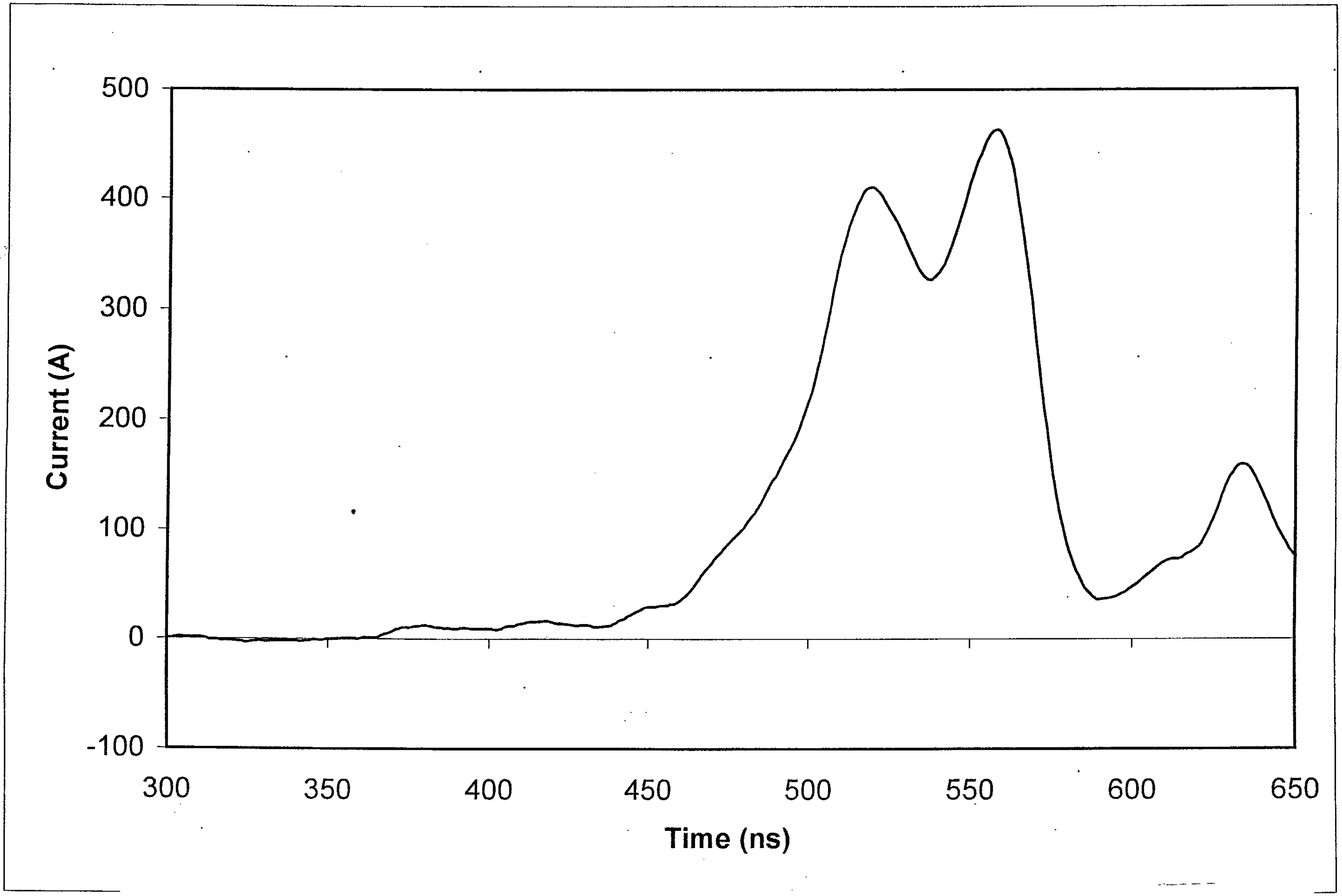

Fig. 3.) c) e-beam current measured at anode (digitally smoothed) for: plasma mode (laser power of 200 W),

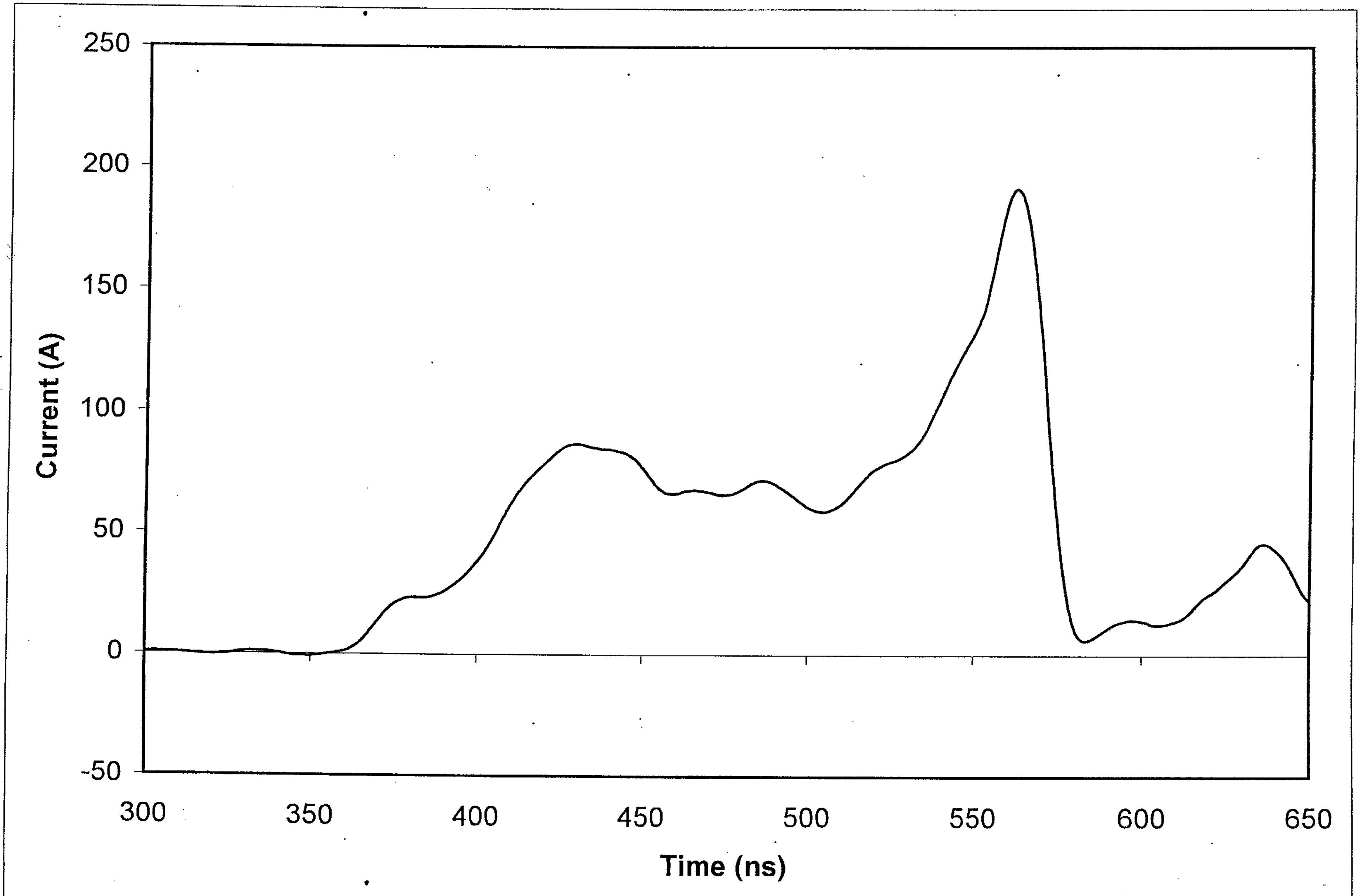

Fig. 3.) d) e-beam current measured at anode (digitally smoothed) for: combined thermionic-plasma mode (laser power of 400 W).

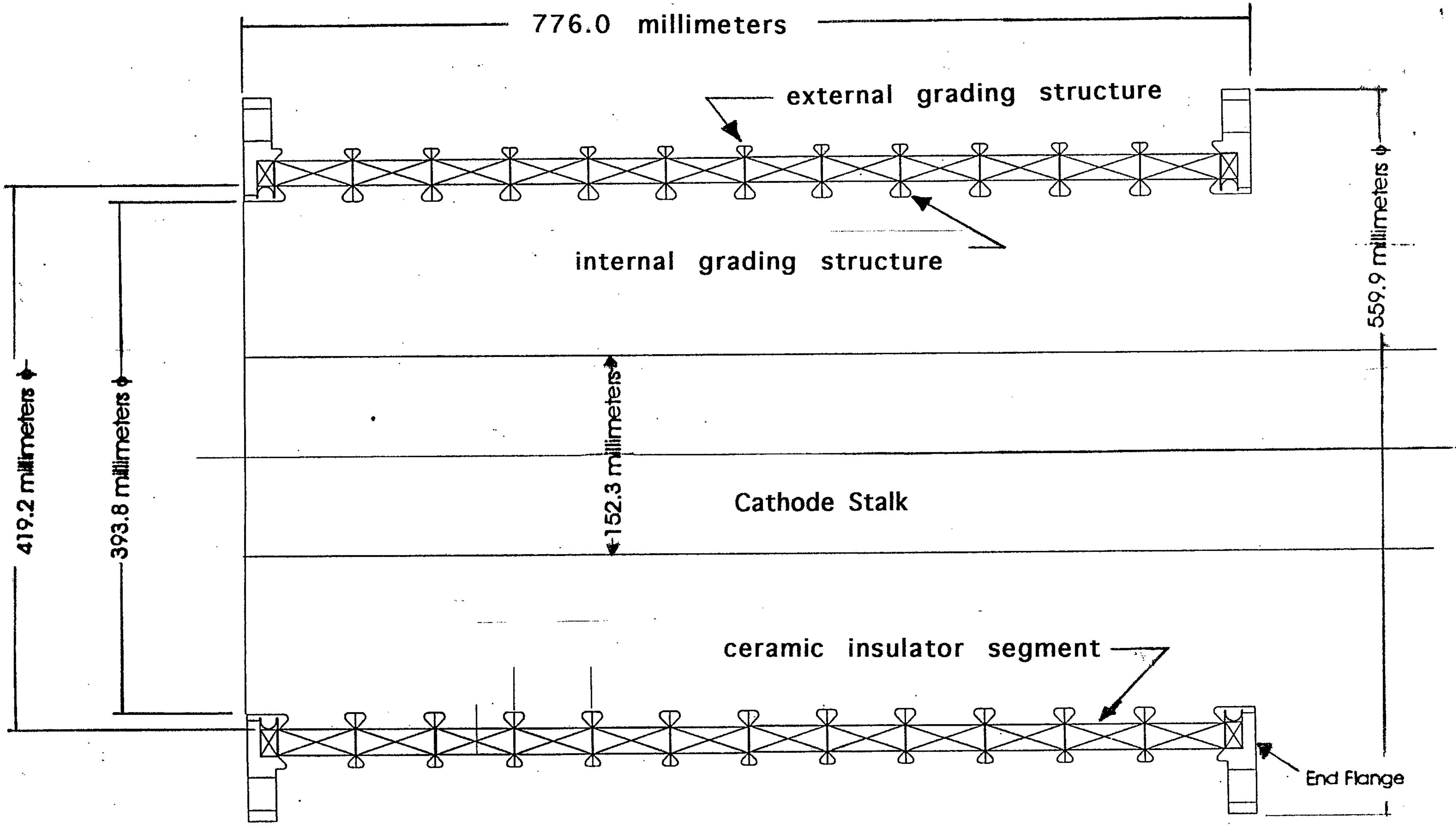

Figure 4 ceramic insulating stack with brazed grading rings. A 12 inch extension spool and adapter plate (not shown) are required to lengthen the insulator stack, because of the straight ceramic rings.

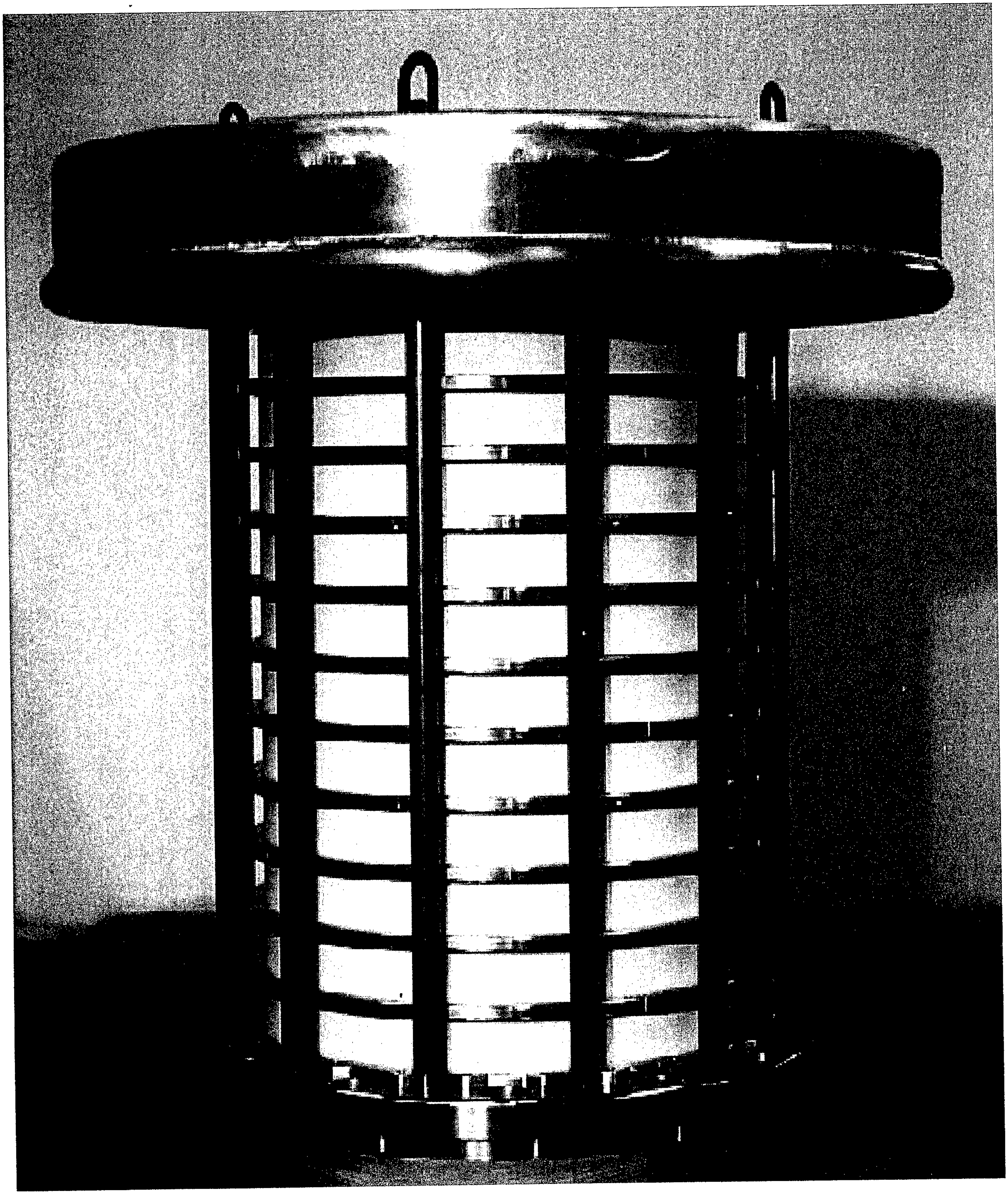

Fig. 5. Photograph of the complete ceramic insulating stack assembly.